

# Radiation-induced re-emission in a 2D electron system.

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**Abstract** – Recent experiments on re-emission of radiation and magnetotransport in photoexcited two-dimensional electron systems are theoretically analyzed. These experiments have concluded that there exists a strong correlation between the re-emitted radiation and the radiation-driven current through the sample. We study these remarkable experimental results using the radiation-driven electron orbit model. According to it, two-dimensional electrons under a magnetic field move back and forth driven by radiation. Therefore, they behave as oscillating dipoles re-emitting part of the radiation previously absorbed. Then, this theory would explain in a simple way the experimental results.

**Introduction.** – Two-dimensional electron systems (2DES) implemented in ultra-high mobility GaAs/AlGaAs heterostructures are called to be part of the key building blocks in the current and future nanoelectronics. Their interaction with radiation and the electron transport through them are of special interest from both theoretical and experimental standpoints. For instance, those systems are potentially useful for electromagnetic wave characterization in the microwave (MW) and terahertz bands with a technological interest that can be considered beyond question. Accordingly, remarkable effects such as microwave-induced resistance oscillations (MIRO) and zero-resistance states (ZRS) have drawn much attention from the condensed matter physics community. These effects were discovered when a high-mobility 2DES in a low and perpendicular magnetic field ( $B$ ) was irradiated with MW [1,2]. Different theories have been proposed to explain these effects [3–9] but the physical origin still remains unclear. In the same way, an important experimental effort has been made too [10–16].

Very recent experimental results [17, 18] on MIRO compare the magnetoresistance ( $R_{xx}$ ) response of the microwave-excited 2DES with the concurrent re-emission from the same system that is detected by a nearby carbon resistor sensor [17,18]. They report on a strong correlation between the results coming from both types of measurements. They also study the dependence on MW frequency and power suggesting a cause and effect relationship between the microwaves on the 2DES and what is observed in the current through the carbon resistor. Another im-

portant result they obtain is that the re-emission signal in the carbon sensor remains unchanged even when the current through the 2DES sample is switched off. The surprising outcome suggests a radiation-induced change in the electronic properties of the 2DES even in the absence of applied current. According to these experiments [17,18], the carbon sensor detects both the incident or primary and the re-emitted radiation. The incident radiation is constant, thus it produces a magnetic field independent change in the carbon resistor. On the other hand, the re-emitted radiation depends on the magnetic field due to the radiation-induced resistance oscillations and cyclotron resonance, both in the 2DES. Therefore for experimentalists, it is easy to tell the difference between incident and re-emitted signals [17,18].

In this letter, we theoretically study the physical origin of these experimental results and their dependence on MW frequency, power and dc-current. We focus on the re-emitted radiation and study the concurrence between both transport data from the GaAs/AlGaAs heterostructure and from the carbon resistor sensor. We also predict about the re-emission process from the 2DES and its effect on the carbon resistor signal when the 2DES undergoes a regime of ZRS. We are based on a previous theoretical model developed by the authors to deal with MIRO and ZRS [3,4,19–23]: *the radiation (or MW) -driven electron orbits model*. According to this theory, two-dimensional electrons under a static magnetic field, i.e., two dimensional electron orbits, oscillate being spatially driven by radiation. Therefore, they behave as oscillating dipoles re-

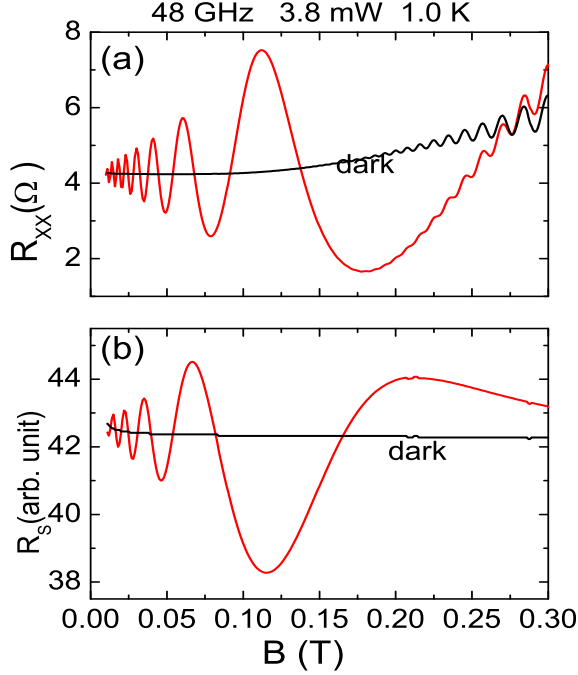


Fig. 1: (Color online). a) Calculated longitudinal magnetoresistance,  $R_{xx}$ , vs magnetic field with (red curve) and without (black curve) 48 GHz, MW irradiation. b) Calculated magnetoresistance in the carbon resistor,  $R_s$ , versus magnetic field with (red curve) and without (black curve) re-emitted radiation from the 2D GaAs/AlGaAs heterostructure.

emitting part of the radiation previously absorbed. Then, this theory would explain in a simple way the experimental results [17, 18].

**Theoretical model.** – The above mentioned theory [3, 4, 19] was proposed to explain the  $R_{xx}$  of an irradiated 2DES at low  $B$ . We obtained the exact solution of the corresponding electronic wave function:  $\Psi(x, t) \propto \phi_n(x - X - x_{cl}(t), t)$ , where  $\phi_n$  is the solution for the Schrödinger equation of the unforced quantum harmonic oscillator,  $X$  is the center of the orbit for the electron motion,  $x_{cl}(t)$  is the classical solution of a forced harmonic oscillator:

$$x_{cl}(t) = \left[ \frac{eE_0}{m^* \sqrt{(w_c^2 - w^2)^2 + \gamma^4}} \right] \cos wt = A \cos wt \quad (1)$$

where  $e$  is the electron charge,  $\gamma$  is a phenomenologically-introduced damping factor for the electronic interaction with acoustic phonons,  $w_c$  the cyclotron frequency and  $E_0$  the MW-radiation electric field. Then, the obtained wave function is the same as the standard harmonic oscillator where the center is displaced by  $x_{cl}(t)$ . Thus, the orbit centers are not fixed, but they oscillate harmonically at the radiation field frequency  $w$ . This *radiation – driven*

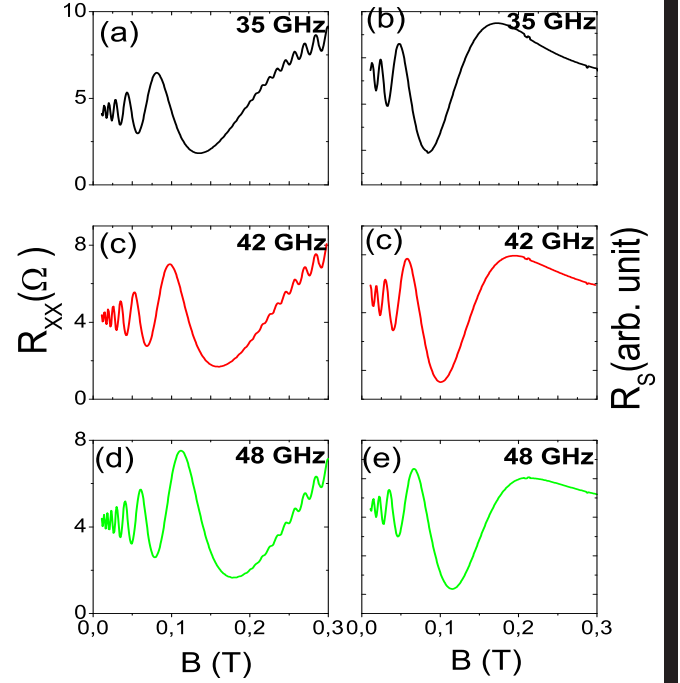


Fig. 2: (Color online). Left panels show the longitudinal resistance  $R_{xx}$  vs the magnetic field  $B$ . Right panels show the carbon sensor resistance  $R_s$  vs  $B$ . Calculated results correspond to different frequencies: 35, 42 and 48 GHz. For all curves we observe how the oscillatory structures span to higher  $B$  as the MW-frequency increases. In the same way more oscillations are obtained.

behavior affects dramatically the charged impurity scattering and eventually the conductivity. Then, first we calculate the impurity scattering rate  $W_{n,m}$  [3, 4, 19] between two *oscillating* Landau states  $\Psi_n$ , and  $\Psi_m$ . Next we find the average effective distance advanced by the electron in every scattering jump:  $\Delta X^{MW} \propto A \cos w\tau$ , where  $\tau = 1/W_{n,m}$  is the scattering time [3, 4, 19]. Finally the longitudinal conductivity  $\sigma_{xx}$  is given by:  $\sigma_{xx} \propto \int dE \frac{\Delta X^{MW}}{\tau}$  being  $E$  the energy. To obtain  $R_{xx}$  we use the relation  $R_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \simeq \frac{\sigma_{xx}}{\sigma_{xy}^2}$ , where  $\sigma_{xy} \simeq \frac{n_i e}{B}$  and  $\sigma_{xx} \ll \sigma_{xy}$ . Finally it turns out that  $R_{xx} \propto A$  and then the amplitude of MIROs mainly depends on  $A$ .

One of the most important outcomes of the present theory is that the electron orbits undergo a classical back and forth motion through  $x_{cl}$  driven by the MW. Accordingly, the time-dependent x-coordinate of the guiding center,  $X^{MW}(t)$  performs this harmonic motion because  $X^{MW}(t) = x_{cl}(t)$ . Therefore, each electron orbit behaves as an oscillating electric dipole where the dipole moment  $\Pi$  changes as  $\Pi = eX^{MW}(t) = \Pi_0 \cos wt$  where  $\Pi_0 = eA$ . According to classical electromagnetism, this oscillating

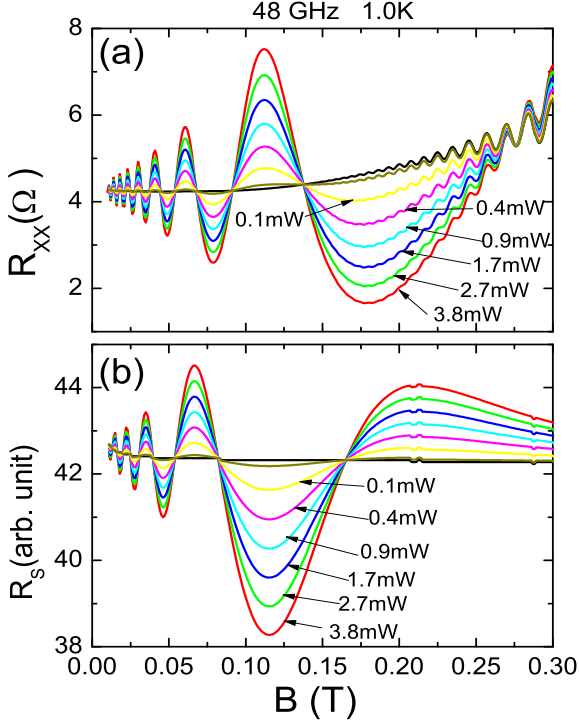


Fig. 3: Dependence on the MW-power of the, a) calculated longitudinal magnetoresistance,  $R_{xx}$ , vs magnetic field, and b) calculated magnetoresistance in the carbon resistor,  $R_s$ , versus magnetic field. The MW-power is swept from 3.2 mW to dark. MW-frequency is 48 GHz and temperature  $T=1.0\text{K}$ . It is clearly observed that MW illumination affects similarly both types of measurements: the radiation-response vanishes as the MW-power decreases.

dipole is able to re-emit radiation at the same frequency of MW. The time dependent electric field  $E_S$  of this re-emitted radiation coming out from one of these oscillating dipoles is given by [24]

$$\begin{aligned} E_S &= \left[ \frac{\Pi_0 \omega^2}{4\pi\epsilon_0\epsilon_{GaAs}z_0c_{GaAs}^2} \right] \cos \omega t \\ &= \left[ \frac{eAw^2}{4\pi\epsilon_0\epsilon_{GaAs}z_0c_{GaAs}^2} \right] \cos \omega t \\ &= E_{S0} \cos \omega t \end{aligned} \quad (2)$$

where  $c_{GaAs}$  is the speed of light in GaAs,  $\epsilon_{GaAs}$  is the GaAs dielectric constant,  $\epsilon_0$  is the dielectric constant in vacuum and  $z_0$  is distance between the 2DES and the carbon resistor. The total electric field of the radiation illuminating the carbon resistor will be the sum of all individual electric fields coming out from each oscillating dipole (oscillating electron orbit) in the 2DES. Since all electron orbits oscillate in phase we can express the total

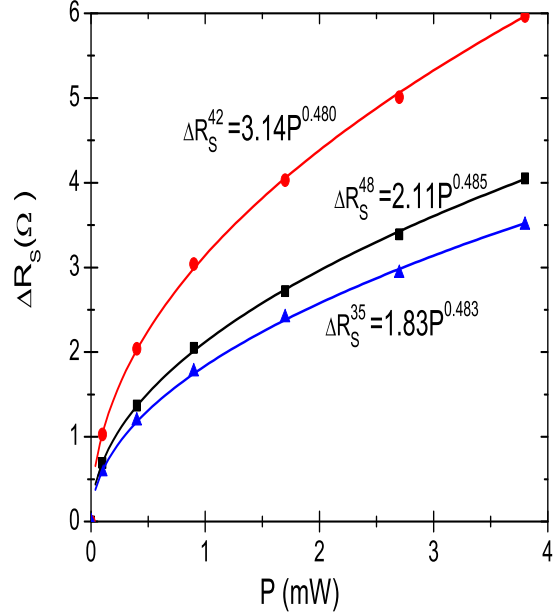


Fig. 4: Calculated  $\Delta R_s = R_s(E_{ST}) - R_s(0)$  vs the MW power  $P$ , for frequencies of 35, 42, 48 GHz.  $R_s(E_{ST})$  is the calculated  $R_s$  for the irradiated carbon sensor and  $R_s(0)$  without irradiation. Three corresponding fits show up in the panel suggesting a square root dependence of  $R_s$  versus  $P$ .

electric field as,

$$E_{ST} = \sum_i (E_S)_i = NE_{S0} \cos \omega t \quad (3)$$

where the subindex  $i$  in the sum denotes the individual oscillating orbits.  $N$  is the total number of electron orbits contributing to  $E_{ST}$ , being  $N = nS$ , where  $n$  is the 2D electron density and  $S$  the surface of the sample. This theory obtains, in agreement with experiments, that the electric field amplitude of the re-emitted radiation,  $NE_{S0}$ , depends on the magnetic field through  $A$  and in turn on  $\omega_c = \frac{eB}{m^*}$ . On the other hand, the electric field amplitude,  $E_0$  of the primary MW radiation illuminating the sensor, is constant, i.e., independent of the magnetic field.

Equation [3] suggest a remarkable fact as it is that the re-emitted radiation could be a possible example of *superradiance*. Superradiance [25] is a cooperative phenomenon in which the radiation coming from an ensemble of  $N$  microscopic emitters in phase with each other is substantially enhanced. Two main conditions have to be fulfilled in order to obtain superradiance: first the distance between emitters has to be much smaller than the radiation wavelength and second, the net electromagnetic field emitted by whole ensemble has to be proportional to  $N$ . Therefore the emitted intensity goes as  $N^2$ . Based in our theoretical approach we can state that the re-emitted radiation in the corresponding experiments [17,18], fulfills all the

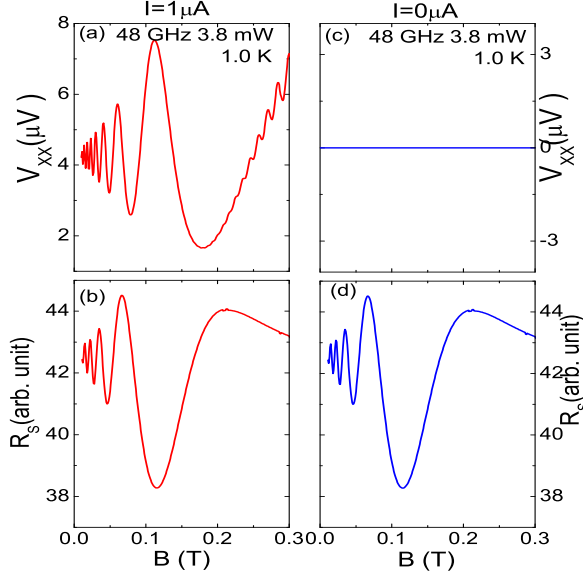


Fig. 5: Calculated longitudinal voltage  $V_{xx}$  and carbon sensor resistance,  $R_S$  vs magnetic field for different values of the DC current  $I$ , under 48 GHz MW irradiation. In panels a) and b) the dc-current through the 2DES is  $I = 1 \mu\text{A}$ . In c) and d),  $I = 0 \mu\text{A}$ . Remarkably,  $R_S$  turns out to be immune to the applied current through the sample.

requirements to be considered as an example of *superradiance*. The distance between Landau states (emitters) is much smaller than the MW wave length and according to equations [3] the net electromagnetic field goes as  $N^2$ . This prediction could be easily confirmed in an experiment with a sample of tunable electron density via a voltage gate. In this way, it could be studied the dependence of the re-emitted intensity with the electron density, i.e., the number of emitters, and to check out if intensity goes as the square of the electron density.

To calculate the conductivity and resistance,  $R_S$ , of the carbon resistor under irradiation, as a first approach, we extend the radiation-driven electron orbit model to the resistor. The electrons inside the resistor contributing to the current are subjected to the same  $B$ , turning into quantum oscillators. Therefore we approximate them as 2D-electrons which are able to be coupled to radiation and spatially driven by it. It is not intended in the current letter to present a microscopical model for the current through the carbon sensor in the presence of a magnetic field. We rather focus on how the re-emitted radiation couples with the electrons in the sensor and study the MW-mediated strong correlation between carbon sensor and GaAs-2DES.

We expect to obtain, in agreement with experiments, an oscillating profile for  $R_S$  versus magnetic field. According to our theory, the electric field of radiation illu-

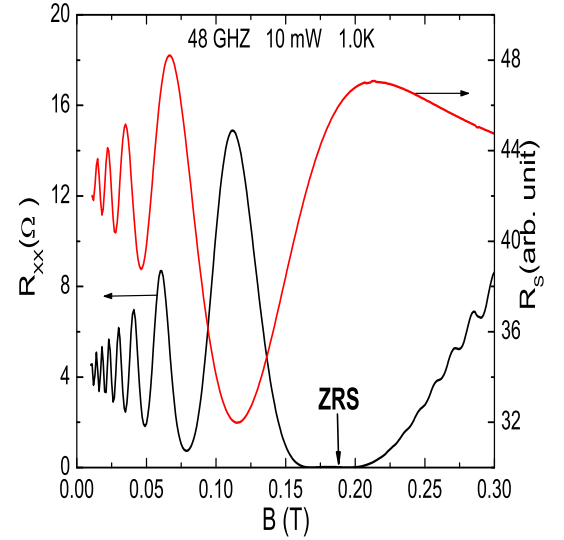


Fig. 6: Calculated  $R_{xx}$  under MW-irradiation of high power (left  $y$ -axis) and  $R_S$  (right  $y$ -axis) versus  $B$ . It is observed that the radiation-related features of  $R_S$  are not affected by the existence of a ZRS regime in  $R_{xx}$  around  $B = 0.18$  T.

minating the resistor is given by  $E_{ST}$ , which implies that  $R_S \propto E_{ST}$ . Then, the oscillation frequency of the electron orbits in the resistor will be the same as the MW-frequency. On the other hand, the oscillations amplitude of the oscillatory structure obtained from the sensor will mainly depend on  $NE_{S0}$ , that plays the role of  $E_0$  for MIROs. This will be reflected in the radiation response measured in  $R_S$ . Another different feature in the case of the resistor is the impurity scattering rate,  $W_S$ . In our approximation we consider that the conductivity is worse in the carbon resistor than in the GaAs-2DES and then the scattering rate will be bigger and the scattering time smaller:  $W_S > W_{n,m}$  and  $\tau_S < \tau$ ,  $\tau_S$  being the impurity scattering time in the resistor and related with the scattering rate by  $\tau_S = 1/W_S$ . For the numerical calculations we have phenomenologically assumed that  $W_S \simeq 2 \times W_{n,m}$  and then  $\tau_S \simeq 0.5 \times \tau$ .

**Results.** — In Fig. 1 we present in the upper panel, calculated diagonal magnetoresistance  $R_{xx}$  of the 2DES and in the lower panel, calculated carbon sensor resistance,  $R_S$ , in both cases with respect to  $B$ . The dark case is also presented for both panels, turning out to be featureless: for the upper panel MIRO are not obtained, as expected, and for lower panel there is only a flat line. But when MW of 48 GHz is switched on, we observe MIRO in the upper panel, and for the lower one we observe important radiation-related oscillatory features that we can consider concurrent with the obtained MIRO in the 2DES. In Fig. 2, we exhibit  $R_{xx}$  and  $R_S$  responses for different MW-frequencies. Left column presents  $R_{xx}$  vs  $B$  for 35, 42

and 48 GHz. We observe that MIROs span to higher  $B$  as the MW-frequency is increased and at the same time more oscillations turn up. In the right column we present the concurrent carbon sensor response  $R_S$  vs  $B$  for the same frequencies as in the left column. Similarly as in the experiments and the left column, we observe that as MW-frequency increases more oscillations show up and they span to higher  $B$ . All these features suggest that the carbon sensor signal correlates to the response of the 2DES to MW irradiation.

In Fig. 3 we present the MW-power dependence of  $R_{xx}$  and  $R_S$  versus  $B$ . The frequency of MW is 48 GHz. The MW-power is swept from 3.2 mW to dark. Remarkably, we obtain similar evolution for both types of measurements: for all curves the radiation response is getting lower as the MW-power decreases. It is also interesting to highlight that the oscillations phase for  $R_{xx}$  does not change with the MW-power. And it happens the same with  $R_S$  whose oscillations phase remains unchanged for different MW powers. In other words, as MW power increases the amplitude of the oscillatory features becomes bigger for both  $R_{xx}$  and  $R_S$ , but their relative position on the x-axis are fixed. We have used the above results to confirm further the radiation-mediated correlation between the 2DES and the detected signal in the remote carbon resistor. Therefore, in Fig. 4 we exhibit  $\Delta R_S = R_S(E_{ST}) - R_S(0)$  vs the MW power  $P$ , where  $R_S(E_{ST})$  is the calculated  $R_S$  for the irradiated carbon sensor and  $R_S(0)$  without irradiation. As in experiments, we obtain that the power dependence of  $\Delta R_S$  oscillations for all frequencies can be fit with a sublinear power law function  $\Delta R_S = \Theta P^\alpha$ , where  $\Theta$  and  $\alpha$  are fit parameters. The parameter  $\Theta$  vary with the MW-frequency but for the exponent we expect that  $\alpha \simeq 0.5$ , as it is obtained in the experiments.

The explanation can be obtained straightforward from the theory. The radiation power,  $P$ , can be related with  $A$  through the well-known formula that gives radiation intensity  $I$  (power divided by surface) in terms of the radiation electric field  $E_0$ :  $I = \frac{1}{2}c\epsilon_0 E_0^2$ , where  $c$  is the speed of light in vacuum and  $\epsilon_0$  is the permittivity in vacuum. If we want to express only the power in terms of the radiation electric field we have to take into account the sample surface. In the particular case of GaAs we can readily obtain:  $P = \frac{1}{2}c_{GaAs}\epsilon\epsilon_0 E_0^2 S$  where  $c_{GaAs}$  is the speed of light in GaAs and  $\epsilon$  is the GaAs dielectric constant. Accordingly,  $E_0 \propto \sqrt{P}$  and in turn  $E_{S0} \propto \sqrt{P}$  too. Then, eventually we obtain that  $R_S$  varies with  $P$  following an square root law:  $R_S \propto \sqrt{P}$ . Thus, we expect that the exponent of the sublinear law will be  $\alpha \simeq 0.5$ .

In Fig. 5, we present the dependence on the dc-current of the MW-response in the longitudinal voltage  $V_{xx}$  and  $R_S$  versus  $B$ . The MW-power remains unchanged. In Figs. 5a and 5b we describe similar magnetoresistance oscillations as in previous figures for  $R_{xx}$  and  $R_S$ . Figs. 5c and 5d correspond to a situation where the applied dc-current is switched off. As expected, the  $V_{xx}$  MW response vanishes. However, the radiation-induced variation

of  $R_S$  still persists when the MW illumination continues to be applied to the 2DES. Remarkably, this indicates that there is a MW effect on the 2DES even in the absence of dc current according to the obtained response in the carbon resistor. This result demonstrates also the strong correlation between the irradiated 2DES and the carbon resistor. We have to stand out that  $R_S$  turns out to be immune to the applied current through the sample. In Fig. 6 we present in the same panel, calculated  $R_{xx}$  under MW-irradiation of high power (left y-axis) and  $R_S$  (right y-axis) versus  $B$ . Here we want to contrast the  $R_S$  response when  $R_{xx}$  undergoes a regime of ZRS. We observe that the radiation-induced features in the  $R_S$  curve are totally unaffected by the existence of ZRS in  $R_{xx}$ . Radiation-assisted ZRS is mainly a transport-related effect, however it does not cause any effect on how the radiation is re-emitted by the 2DES. Then, this result is in agreement with the one exhibited in Fig.5, in the the sense that the re-emission process from the 2DES is totally unaffected by the transport process through the sample. To date, this kind of experiment has not been carried out yet. We think that the corresponding experimental results would mean a possible way to validate and give credibility to the existing theoretical models on MIRO and ZRS.

**Conclusions.** — In conclusion, we have theoretically analyzed recent experiments on re-emission of radiation in photoexcited two-dimensional electron systems. These experiments have shown that there exist a strong correlation between the re-emitted radiation and the radiation-driven current through the sample. We study these experimental results using the radiation-driven electron orbits model. According to it, two-dimensional electrons under a magnetic field move back and forth driven by radiation. Therefore, they behave as oscillating dipoles re-emitting part of the radiation previously absorbed. Then, this theory would explain in a simple way the experimental results. We also studied the dependence of re-emission on MW-frequency, MW-power and dc-current through the 2DES. In the case of the power dependence we obtain a sublinear power law where the exponent is around 0.5 as in the experiments. We are able to trace this exponent and power law using the theoretical model. We also obtain calculated results on re-emission and transport trough the carbon resistor when the 2DES undergoes a regime of ZRS. We predict that this regime does not affect the process of re-emission from the 2DES.

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